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Organic carbon content and its liable components in paddy soil under water-saving irrigation

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ABSTRACT

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Variation of soil organic carbon (SOC) and its liable fractions under non-flooding irrigation (NFI) were investigated. In NFI paddies, the soil microbial biomass carbon (SMBC) and water extractable organic carbon (SWEC) content in 0–40 cm soil increased by 1.73–21.74% and 1.44–30.63%, and SOC in NFI fields decreased by 0.90–18.14% than in flooding irrigation (FI) fields. As a result, the proportion of SMBC or SWEC to SOC increased remarkably. It is attributed to the different water and aeration conditions between FI and NFI irrigation. The non-flooding water-saving irrigation increased soil microbial activity and mineralization of SOC, which broke down more soil organic nutrients into soluble proportion and is beneficial for soil fertility, but might lead to more CO_2 emission and degradation in carbon sequestration than FI paddies.

Keywords: water management; drying-wetting cycle; precipitation; soil carbon sequestration; soil respiration

Soil organic carbon (SOC) plays an important role in soil-atmospheric CO_2 exchange, soil fertility and sustainability (Tiessen et al. 1994, Lal 2004, Pospíšilová et al. 2011). The soil microbial biomass carbon (SMBC) and water extractable organic carbon (SWEC) are relatively easily decomposable part and respond more rapidly to different tillage or residual management practice than SOC, and are potentially more sensitive indicators of agricultural management-induced changes (Li et al. 2016). The contents of SMBC and SWEC are highly related to the activity of soil microorganisms and other environmental factors such as soil moisture, soil aeration, and temperature (Franzleubbers et al. 2001, Butenschoen et al. 2011, Tiemann et al. 2011).

Soil moisture is a key factor affecting microbial activity and carbon (C) mineralization (Moyano et al. 2013). Soils always undergo drying-wetting cycles after irrigation or precipitation. And the drying-wetting cycle conditions can influence soil physical and chemical properties, soil microbial activity and SOC mineralization. Numerous laboratory experiments suggested that drying-wetting cycles can improve the mineralization of soil organic matter (SOM) (Fierer et al. 2002, Yao et al. 2011, Gao et al. 2016), partially due to the increased microbial activity upon rewetting of dry soil (Van Gestel et al. 1993, Gordon et al. 2008), and partially due to soil aggregate structure destruction and increased exposure of SOM (Denef et al. 2001, Cosentino et al. 2006). However, some studies showed no change or even a decrease in soil carbon mineralization under drying-wetting conditions compared to constant soil moisture. Franzleubbers et al. (2001) found repeated drying-wetting of cowpea residue-amended soil reduced

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microbial activity. Mikha et al. (2005) found repeated drying and rewetting reduced soil cumulative mineralized C, because the increase in C mineralization rate after rewetting was not sufficient to compensate its reduction in the drying period. This divergence in the results is probably due to the duration of the wetting and drying periods and different experimental techniques (Borken and Matzner 2009).

Paddy soil is an anthropogenic soil, and its evolvement and formation are affected greatly by tillage, water and fertilization management. Generally, flooding in rice paddies favoured soil carbon accumulation compared with upland soil, and resulted in high SOC contents in long-term (Xu et al. 2013). To cope with water scarcity, non-flooding irrigation (NFI) has been used in rice field, recently. The effects of NFI on SOC transformation in paddy soil are urgent to be investigated.

Most previous studies on effect of drying-wetting cycles on SOC transformation were conducted by laboratory incubation, and a good understanding of the effect of these cycles on C mineralization under field condition is required. Yet, there are few results carried out in paddy field irrigated with a drying-wetting irrigation regime. Assuming that the drying-wetting cycle would result in a change in soil SOC contents and its liable components, SOC, SMBC and SWEC contents were observed in a rice field under non-flooding irrigation and flooding irrigation (FI) in east China, in order to investigate the effects of NFI water regimes on SOC transformation in paddy soil and its implication on soil fertility, soil carbon storage and global greenhouse gas emission.

MATERIAL AND METHODS

Site description. The study was conducted in rice paddies at the Kunshan irrigation and drainage experiment station (31°15'15"N, 120°57'43"E) in east China. The soil is Gleyic-Stgnic Anthrosols, developed from alluvial deposits. Soil texture in 0–20 cm is clay, with total nitrogen, phosphorus and potassium contents of 1.7, 1.4 and 20.8 g/kg, respectively. Soil bulk density is 1.3 g/cm^3 and pH is 7.4. The rice was transplanted with 13 cm × 25 cm hill spacing on 25 June, and harvested on 26 October, 2014.

Experimental design. Two irrigation treatments were set, FI and NFI. A randomized complete block design and three replicates were established in 6 plots. The size of each plot was 3 m × 6 m. In FI fields, 30–50 mm water was maintained after transplanting, except during drying in the later tillering or yellow maturity (YM). In NFI fields, 5–25 mm water was kept during the first 7–8 days after transplanting (DAT) in re-greening. In other stages, irrigation was applied only to saturate soil, and standing water was avoided except during period of rain harvesting, pesticide or fertilizer application. The lower thresholds for irrigation were 70, 65, 60, 70, 75, 80 and 70% of saturated soil moisture in early tillering, middle tillering, later tillering, jointing, booting, earing to sprouting (ES) and milk maturity (MM) stages. It was fertilized according to the local conventional fertilization practice.

Field measurements. Irrigation water volumes were recorded by water flow meters. Soil moisture was monitored with three replicates using a time domain reflectometer (TDR, Soil moisture, Goleta, USA) and waveguides installed at 0–20 cm and 20–40 cm depths. Water depth was monitored using vertical rulers fixed in the field. Daily meteorological data, including precipitation, wind speed, temperature, radiation, and relative humidity were recorded by an automatic weather station (ICT, Armidale, Australia). Soil redox potentials (Eh) at 0–10 cm depth were measured using oxidation-reduction potential meters, with three replicates *in situ*.

Soil sampling and analysis. Soil samples were collected from each plot following an S-shaped pattern at 0–10, 10–20, and 20–40 cm depths in stages of ES, MM and YM. Then samples from the same depth were homogenized by mixing and separated from debris and crop residues. One part of the fresh samples was stored at 4°C, another part was air dried, grounded and sieved by a 0.149 mm sieve. The 12.5 g fresh soil samples were used for SMBC measurement by chloroform fumigation extraction method (Vance et al. 1987), and another 12.5 g fresh soil samples for SWEC measurement were placed into conical flask and immersed into 50 mL 0.5 mol/L K_2SO_4 solution, then shaken for 30 min before extracts were separated by using the 0.45 μm filter (Sparling et al. 1998). For SOC measurement, 0.5 g air dried soil samples were oxidized with 0.08 mol/L $K_2Cr_2O_4$ and H_2SO_4 at 180°C, and titrated by 0.2 mol/L $FeSO_4$ with Ferroin as indicator.

Statistical analysis. All data were preliminary analysed using Excel 2007 (Microsoft, Redmond, USA). SPSS19.0 (IBM SPSS Statistics, Armonk, New York, USA) was used for difference analysis (*LSD* test with significant level of $P = 0.05$).

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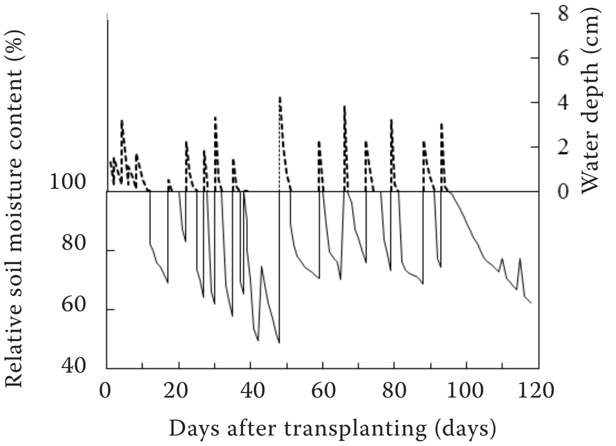

Figure 1. Water depth and soil moisture in non-flooding irrigation rice fields

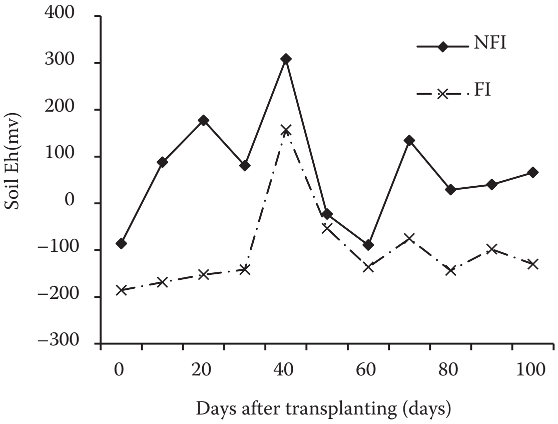

Figure 2. Soil redox potentials (Eh) in rice fields under different water managements. NFI – non-flooding irrigation; FI – flooding irrigation

RESULTS

Soil moisture and Eh values. In NFI paddies, there were more than 10 times of drying process, and about half of the rice season was non-flooded (Figure 1). That consequently led to huge change in soil Eh. Soil Eh at 0–10 cm depth ranged from −89.3 to +308.2 mV in NFI fields, much higher than those in FI fields (from −185.8 to +156.9 mV) (Figure 2). It is clear that drying in NFI fields frequently caused an increase in soil Eh.

SOC contents. Generally, SOC in paddy soil with different irrigation treatments reduced along with soil depth, and SOC in NFI soil was slightly lower (0.90–18.14%) than in FI soil (Figure 3). The SOC contents in 0–10 cm NFI soil were 12.15, 12.89 and 13.07 g/kg in stage of ES, MM and YM, 0.87, 0.21 and 1.14 g/kg lower than those in FI field, respectively. For soil in 10–20 cm and 20–40 cm, the SOC contents in NFI soil were also slightly lower than those in FI soil. It can be concluded that NFI led to slightly reduced SOC contents than in FI soil, but most of the difference is not significant, except for SOC in 10–20 cm soil in ES stage.

SMBC contents. The SMBC in paddy soil with different irrigation treatments reduced along with the increase in soil depth (Figure 4a). Compared with the SMBC in 0–10 cm soil, the SMBC contents in 20–40 cm soil were 54.64, 137.15 and 153.2 mg/kg lower in NFI fields, and were 37.5, 130.69 and 187.47 mg/kg lower in FI fields. In NFI soil, the SMBC contents were 173–21.74% higher than those in FI, with about half of the differences significant. Especially in 0–10 cm NFI soil, the SMBC contents were 388.15, 434.84 and 425.09 mg/kg in stages of ES, MM and YM; those were 79.32, 40.49 and 7.24 mg/kg higher than those in FI soil. For deep soil in 10–20 cm and 20–40 cm, the SMBC contents in NFI soil were also slightly higher than those in FI soil. It can be concluded that NFI irrigation resulted in higher SMBC contents than FI irrigation.

Soil SMBC accounted for a little proportion (2.41–3.61%) of SOC (Figure 4b). Since the SOC contents in NFI soil were lower than in FI soil, on the contrary the SMBC contents were higher in NFI soil. As a result, the proportion of SMBC to SOC is higher in NFI soil (2.68–3.61%) than in FI soil (2.41–3.07%). And most of the differences in

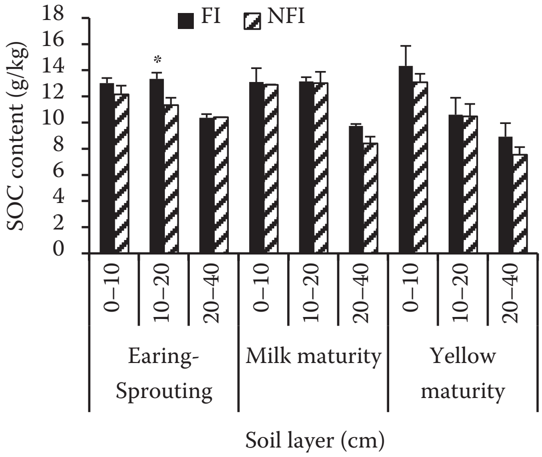

Figure 3. Soil organic carbon (SOC) contents in different soil depth in non-flooding irrigation (NFI) and flooding irrigation (FI) paddy fields. *indicates the difference between NFI and FI is significant at $P < 0.05$)

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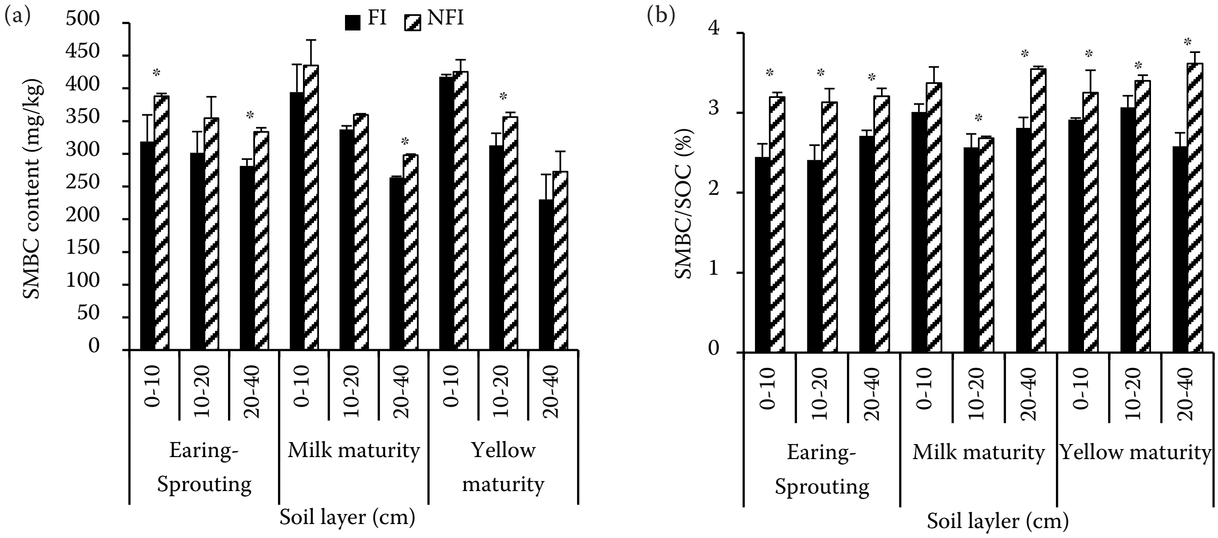

Figure 4. (a) Soil microbial biomass carbon (SMBC) contents and (b) it proportion to soil organic carbon (SOC) in different soil depth in non-flooding irrigation (NFI) and flooding irrigation (FI) paddy fields. *indicates the difference between NFI and FI is significant at $P < 0.05$

the proportions of SMBC to SOC between NFI and FI were significant ($P < 0.05$).

SWEC contents. SWEC contents in paddy soil with different irrigation treatments were also high in surface soil, and reduced along with the increase in soil depth (Figure 5a). Compared with SWEC contents in 0–10 cm soil, the SWEC contents in 20–40 cm soil were 28.98, 130.92 and 71.97 mg/kg lower in NFI fields, and were 47.3, 105.41 and 44.58 mg/kg lower in FI fields. In NFI soil, the SWEC contents were 1.44–30.63% higher than those in FI fields. And the difference in SWEC contents between NFI and FI was significant in 0–10 cm surface soil, but not in deep soil. The SWEC contents in 0–10 cm NFI soil were 228.57, 296.92 and 232.32 mg/kg in stages of ES, MM and YM, those were 28.48, 29.33 and 29.68 mg/kg higher than those in FI soil, respectively. It can be concluded that NFI irrigation resulted in higher SWEC contents than in FI soil.

SWEC accounted for an even lower proportion (1.41–2.30%) of SOC than SMBC (Figure 5b). As a result of increased SWEC and reduced SOC in NFI soil, the proportion of SWEC to SOC is higher in NFI soil (1.69–2.30%) than in FI soil (1.41–2.04%), and most of the differences in the

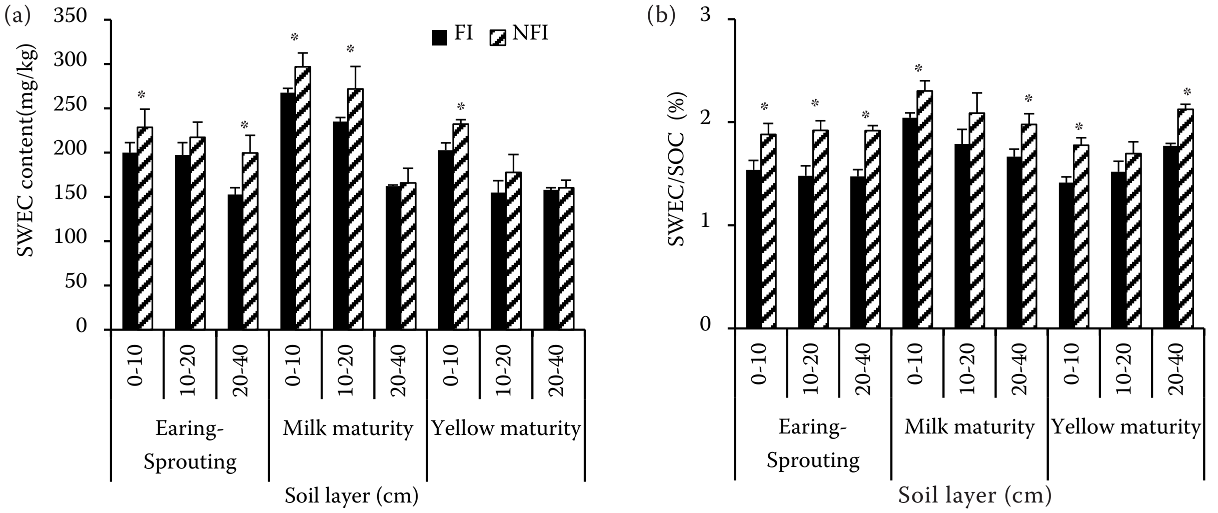

Figure 5. (a) Water extractable organic carbon (SWEC) contents and (b) it proportion to soil organic carbon (SOC) in different soil depth in non-flooding irrigation (NFI) and flooding irrigation (FI) paddy fields. *indicates the difference between NFI and FI is significant at $P < 0.05$

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proportions of SMBC to SOC between NFI and FI were significant ($P < 0.05$).

DISCUSSIONS

Effect on SOC and its fractions. In NFI irrigated rice fields, soils undergo frequently a drying-wetting process (Figure 1). In NFI soil, the SMBC and SWEC contents increased, but SOC contents decreased (Figures 3–5). Thus, water-saving irrigation is favourable to the increase of SMBC and SWEC, but might lead to lower SOC contents. It indicated that the frequently implied drying-wetting process favoured the soil microorganism and led to high mineralization of SOC. It agreed with some researchers who observed increases of soil microbial activity and C mineralization under drying-wetting condition by incubation experiments (Fierer et al. 2002, Zhao et al. 2011). The decrease in SOC contents can also be attributed to destruction of soil aggregate upon drying wetting cycles (Denef et al. 2001, Cosentino et al. 2006), which increased exposure of SOM (Kemper et al. 1985).

Implications on CO_2 emission. The transformation of SOC is strongly linked with CO_2 emission. The high mineralization rate always accompanied with high soil respiration or CO_2 emission (Orchard and Cook 1983, Mancinelli et al. 2013). Compared with FI paddies, less SOC contents in surface NFI soil indicated that more gaseous C was erupted from soil and released into atmosphere (Zhao et al. 2011). Priemé and Christensen (2001) found that the CO_2 emission rates increased up to 5-fold following wetting or thawing. Thus, the application of NFI irrigation might result in more CO_2 emission than FI irrigation. And the relationship between soil C mineralization and soil respiration should be investigated to reveal the environmental effect of water saving irrigation on rice paddies.

Implications on soil fertility and C sequestration. Other than the problem of high soil respiration, accelerated mineralization of SOC will promote the transformation of soil organic nutrients into water soluble proportion, which is conducive to the soil available fertility. As a result, application of water-saving irrigation is beneficial for soil available fertility, but might lead to degradation in soil C sequestration in long term (Snyder et al. 2009, Linquist et al. 2012). Suitable carbon management, like residue, manure or biochar, should be employed in NFI fields to sustain its soil C sequestration. And biochar, as an innovative carbon management tool (Cernansky 2015), might be a potential choice to realize it. Impact of carbon management on soil fertility, soil C transformation and sequestration, CO_2 emission in NFI soil should be further investigated.

In summary, NFI resulted in higher SMBC and SWEC contents and slightly lower SOC content in surface soil than FI, as a result the proportion of SMBC and SWEC to SOC increased remarkably. It indicates that NFI irrigation can promote the transformation of soil organic nutrients into water soluble proportion. That is beneficial for soil available fertility, but might lead to more CO_2 emission and degradation in soil C sequestration. Therefore, it is urgent to find a new carbon management technology to balance the soil C sequestration and CO_2 emission in NFI paddies, based on the analysis of the impact of water-carbon interaction on soil fertility, CO_2 emission, soil C transformation and sequestration.

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